

Living quicksand

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Abstract The image of quicksand mercilessly swallowing a victim has inspired the fantasy of kids and helped writers and moviemakers to get rid of evil figures. Is this really possible? This is still disputed since till today it is not even clear what quicksand exactly is. In soil mechanics, the “quick-condition” is usually described as a liquefaction due to high water pressure essentially possible with any soil. However, previous studies have detected anomalous rheological properties from natural quicksand. Pushed by these contradicting points of view we set off to Lençóis Maranhenses in North-East Brazil, where quicksands are common, to investigate rheology and strength in situ. We found that along very quiet drying lakes cyanobacteria cement an impermeable crust above a suspension of grains. Beyond a critical pressure, the crust fails releasing water from the collapsing colloidal structure and radically changing the depth dependence of the shear strength from a constant to a linear function. The sedimenting solid fraction and the rapid increase of shear strength can indeed trap an intruder endangering his life if the basin is sufficiently deep. As opposed to some previous studies, we find that this quicksand condition cannot be restored once it has collapsed. Finally, we also show some preliminary results from a contact dynamics model specially designed to mimic the living quicksand behavior.

Keywords Granular matter · Contact dynamics · Simulations · Distinct element method · Quicksand · Collapsible soil · Biomaterial

1 Introduction

The nature and danger of quicksand has been disputed for a long time [1–5]. Despite widespread belief that humans can be swallowed or even sucked in, engineers of soil mechanics have typically asserted that, since the density of sludge is larger than that of water, a person cannot fully submerge [6]. The fluidization of a soil due to an increase in ground water pressure which in fact is often responsible for catastrophic failures at construction sites is called by engineers the “quick-condition” and can theoretically happen to any soil [7–9]. Is this condition, which can be reproduced on rather short time scales, equivalent to the legendary quicksands? Another way of fluidization can be vibrations either from an engine [10] or through an earthquake [11]. Recently Khaldoun et al. [12] have studied natural quicksand brought from a salt lake close to Qom in Iran. They found strong thixotropic behavior, and claim that the presence of salt is crucial. Their samples behaved similarly to artificial quicksand produced in the lab and no strong memory effects have been reported.

2 Experiments

The Lençóis Maranhenses is a natural park in the state of Maranhão in the North-East of Brazil consisting of barchanoid dunes separated by lagoons (Fig. 1) that are pushed inland by strong winds with a velocity of 4–8 m/year [13]. It is well known for its beauty as well as the presence of quicksands in which vehicles have often been trapped and

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Fig. 1 In **a** we show a photograph of the dune field at the Lençóis Maranhenses (Maranhão state, North-East of Brazil) where lagoons like the one shown in **b** form during the rainy season between two adjacent dunes and dry out thereafter. The “living quicksand” is usually found at the shores of these lagoons

oil companies have lost equipment. This quicksand appears at the shore of drying lagoons after the rain season. These lagoons, placed amidst very clean sand, have no inlet or outlet and are exclusively filled by rain water. Their bottom is covered by a soft brown or green sheet of algae and cyanobacteria.

We investigated quicksand at Lat: $2^{\circ}28.76'S$, Long: $43^{\circ}03.53'W$. If the pressure on the surface is not higher than a given threshold value, namely $p_c = 10\text{--}20\text{ kPa}$, it is even possible to walk on it and observe that the surface elastically deforms like a waterbed. These deformations visibly range over meters. If the pressure exceeds p_c , the surface starts to display a network of tensile cracks as seen in Fig. 2. Out of the cracks pours water. The object or person rapidly sinks inside, until reaching the bottom of the basin, which in our case could be up to 1 m deep, and is then trapped within a consolidated soil. Objects less than 1 m long but lighter than water like tables of wood are easily drawn inside and become



Fig. 2 Typical quicksand bed at the shore of a drying lagoon in Lençóis Maranhenses (Maranhão state, North-East of Brazil). Beyond a threshold pressure p_c , the crust of the quicksand breaks in a brittle way leaving a network cracks, and the material collapses. The maximum penetration depth for the human body was not greater than 1 m

nearly impossible to retrieve. We conclude that, if the basin is deeper than 2 m which could possibly happen, a human being might perish.

Once the crust has broken, water and solid phase segregate and the whole structure collapses. This explosion of excess pore-water and repacking of sand grains has been discussed by several authors (see [14] and Refs. therein). We could verify that the solid phase was indeed compacted due to the perturbation as the excess pore water stayed on top of the material. The remaining soil shows pronounced thixotropic behavior similar to the one reported in [12] and releases a gas when strongly agitated. The original status of unperturbed material covered by a crust with waterbed motion cannot be recovered neither artificially nor after waiting a long time. The collapse of the quicksand is irreversible. We conclude that it is not possible to understand this quicksand by only investigating samples in the lab. One has to study it in situ because the sampling itself does already destroy the metastable quicksand condition.

Measurements have been performed by partially covering the quicksand fields with light wood plates. This enabled us to walk on the surface of unperturbed and perturbed quicksand areas without provoking any significant changes on the structure of the system. In Fig. 3 we show the dependence of the shear strength τ on the depth before and after the collapse of the system, measured using a vane rheometer [15] for three different quicksand fields in Lençóis Maranhenses. In the unperturbed case, our results indicate that τ remains approximately constant at $\tau \approx 5.4\text{ kPa}$ up to the bottom of the quicksand basin where it then shows a rapid increase with depth. The collapsed material, on the other hand, shows a linear increase of the shear strength with depth, $\tau(h) = ah$, with $a \approx 1.2\text{ kPa/cm}$. We conclude from our measurements that the quicksand is essentially a collapsing suspension of grains

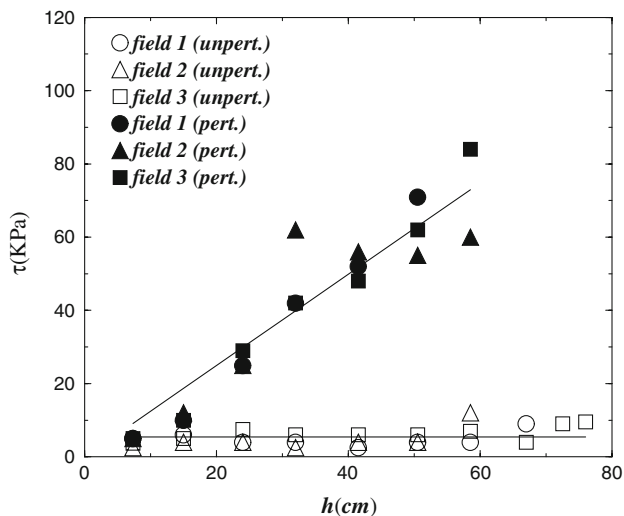


Fig. 3 Dependence of the shear strength τ on depth h before (empty symbols) and after (circles) the collapse of the quicksand for three different quicksand fields in Lençóis Maranhenses. The shear strength has been measured with a vane rheometer [15]. In the perturbed case (i.e., before the collapse), the solid line corresponds to the best fit to the data from all fields of the linear function $\tau = ah$ with $a = 1.2 \pm 0.1$ kPa/cm. The shear strength of the unperturbed quicksand (i.e., before the collapse), however, is approximately $\tau \approx 5.4$ kPa until reaching the bottom of the basin

with depth independent static viscosity. After the collapse, it becomes essentially a soil with shear strength governed by the Mohr–Coulomb friction criterion.

Two questions arise: what produces the impermeable crust enclosing the fluid bubble and how is this crust formed? We

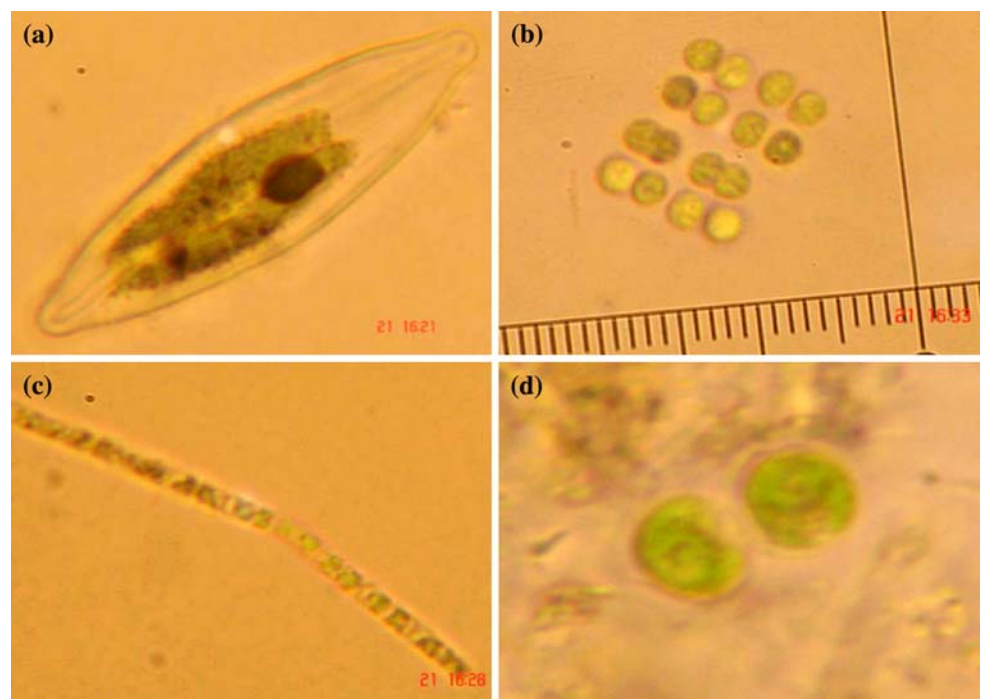
investigated the material of the bottom of the lake, forming the crust and constituting the interior of the bubble physically, chemically and biologically. As shown in Fig. 4, the most visible finding was the huge amount of living *merismopedia*, *cylindrospermopsis* and other cyanobacteria as well as of diatomacea of various types (e.g., *frustulia*) and other eukaryotes. They constitute the largest fraction of mass besides the silicates of the sand. Still water and tropical weather conditions provide them an ideal environment. When the lake dries, they form the quite elastic and rather impermeable crust which hinders further water from evaporating and which therefore just stays below in the bubble. The cementing of soils by cyanobacteria and other algae has in fact already been reported in previous studies [16, 17]. We can therefore conclude that this quicksand is a living structure. We also would like to point out that we found no salt in the water which means that the presence of salt is not a necessary condition to get quicksand, as opposed to the finding of [12].

3 Simulation

In order to illustrate our point that objects lighter than water can be swallowed in the quicksand by the mechanism described above, we also perform computational simulations with a model specially built to represent the physics of an object being pushed inside and subsequently removed from a fragile granular structure.

In our model simulation, we consider a system with width and initial height of 51 and 180 particle diameters,

Fig. 4 Examples of bacteria found in the samples of the “quicksand” **a** diatomacea *frustulia*, **b** a typical colony of *merismopedia*, **c** *cylindrospermopsis racibovskii*, and **d** eukaryote



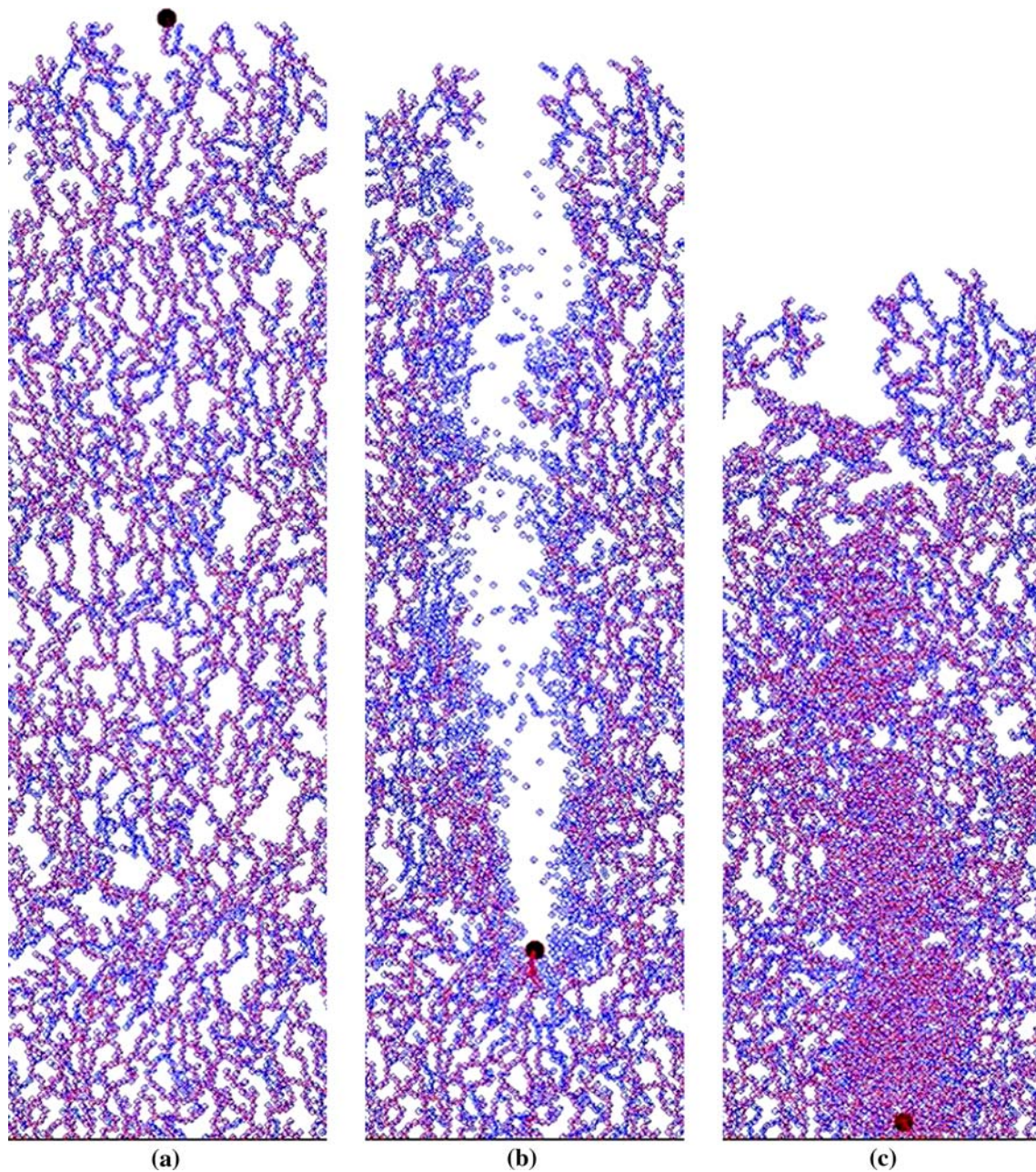


Fig. 5 Three different moments during the penetration process of an intruder into a loose cohesive packing. Before the penetration in **a** we show the unperturbed granular network generated by contact dynamics

[18–20]. In **b** we see the destructive effect caused by the movement of the intruder, while in **c** it finally stops to remain buried under a collapsed mass of grains

respectively, where periodic boundary conditions are applied in the horizontal direction. The unperturbed quicksand is modeled as a granular network consisting of cohesive disks put together through the contact dynamics technique [18, 19] and a ballistic deposition process driven by gravity, as described in [20] and shown in Fig. 5a. After the settlement of all particles, the cohesive forces between them are tuned to the point in which a barely stable structure of grains is assu-

red. This accounts for the slowly drying process of the lakes that results in a tenuous network of grains, like in a house of cards. In our model the surrounding pore water is not explicitly considered but is taken into account as a buoyant medium, thus reducing the effective gravity acting onto the grains. This keeps the model as simple as possible to be able to reproduce the main experimental observations. Of course the details of the collapse of the material may be influenced

by the flow field of the surrounding fluid. In dry quicksand, e.g., it was found experimentally [21,22] that the presence of air leads to a stronger collapse as the falling ball induces an extra flow.

We then proceed with the simulation by pushing a large disk of low density (half of the grain density) at constant force into the granular structure. In Fig. 5 we show a typical simulation of this process. As depicted, the penetration of the disk causes the partial destruction of the porous network and the subsequent compaction of the disassembled material. We observe the creation of a channel (Fig. 5b) which finally collapses over the descending intruder. At the end of the penetration process (Fig. 5c), the larger disk is finally buried under the loose debris of small particles. Since the collapse takes place in a rather short time scale compared to the formation of the quicksand, we assume that no new cohesive bonds are build up instantaneously and that broken cohesive bonds will not have time to recover during penetration.

Our simulations show that the density of the original packing is roughly two-thirds that of the compacted material below which the intruder remains trapped. One should also note that the constant force applied to the disk must exceed a certain value to allow for penetration, otherwise the object will stay above the surface, in agreement with our field experiments. The snapshots shown in Figs. 5a–c have been obtained from model calculations with an applied force that is slightly above the penetration threshold. The further increase of the force does not lead to any substantial changes in these pictures.

To be compatible with our experimental observations, the forces necessary to introduce and remove again the disk should be rather different. Indeed, our results indicate that, if we allow for the cohesive bonds in the material to be completely restored after penetration, the force strength needed to remove the intruder disk after the penetration process can be as much as up to three times higher than the pushing force.

4 Conclusion

In summary, the “living quicksand” studied here can be described as a suspension of a tenuous granular network of cohesive particles. If perturbed, this unusual suspension can drastically collapse, promoting a rapid segregation with water, to irreversibly bury the intruder object. Our simulations indicate that in the worst condition, one could need a force up to three times one’s weight to get out of such morass. Fortunately basins deeper than the human size seem very rare.

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